

High Energy Neutrino Physics with Liquid Scintillation Detectors

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Large liquid scintillation detectors have been generally dedicated to low energy neutrino measurements, in the MeV energy region (as for example, KamLAND and Borexino). Herein we describe the potential employment of large detectors (>1 kiloton) for studies of higher energy neutrinos interactions, from the cosmic rays and as a long baseline neutrino detector. Generally when people have considered large new instruments such as Hanohano and LENA, they have abandoned the possibility of doing useful measurements with higher energy neutrino interactions since these produce enough light to illuminate every photomultiplier tube (PMT), and the scintillation light is isotropic. Here we take into account Fermat's principle, which tells us that indeed the first light to reach the PMTs will be on or near the lightcone, the "Fermat surface", and that directional track information is available. Moreover we have realized that particle type distinction is possible (quasi-elastic muons from electrons). In fact the resolution from a detector of comparable size to SuperKamiokande, may be better in both angle, energy and possibly particle type. This realization opens the doors to a number of applications. Moreover, this capability can be demonstrated with the use of (future) KamLAND detected events in the new long baseline neutrino beam from the Jaeri accelerator in Japan, due to start operations this year. Some of the most attractive possibilities for the future may be in using Hanohano as a moveable long-baseline detector in this same beam, and in the employment of LENA in Europe in future long baseline neutrino beams from CERN. Moreover, in the decision as to what type of detector to use in a future long baseline experiment from Fermilab to the DUSEL underground laboratory at Homestake, consideration should be given to a huge liquid scintillation detector.

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I. INTRODUCTION: THE IDEA

Liquid scintillation based neutrino detectors have now been employed in sizes up to one kiloton, in the KamLAND experiment in Japan[1]. This instrument has been very successful in detecting the inverse beta decay interaction caused by electron anti-neutrinos which arrive, after neutrino mixing, from reactors around Japan. The Borexino experiment in Italy has also measured neutrinos from the sun, detecting the long sought Boron line. This physics involves neutrino events in the energy range of a few MeV. The light output of a scintillation detector is approximately 250 photoelectrons/MeV (PE/MeV) of deposited ionization energy in KamLAND. The light is considered to be isotropic from near the interaction, and one can only fit a time (to nanoseconds), energy (to 5-6%), and rough location (to 10-20 cm) for such events. No event directionality is obtained.¹

The largest underground neutrino detector is the water Cherenkov detector (WC) based SuperKamiokande, also in Japan[2]. While the energy threshold can be fairly low, perhaps 4.5 MeV, the statistics are relatively meager at 10 PE/MeV, despite 13,000 PMTs and 40% coverage of the walls of the cylindrical vessel. The beauty of the Cherenkov technique is however, that one has directionality even at low energies. This has been exploited marvelously by the SuperK group to observe the elastic scattering of electrons by incoming solar electron neutrinos, and these point sharply back towards the sun. But this low energy capability still has not been enough to detect the low energy events such as the neutron capture on hydrogen which takes place in the 2.2 MeV delayed event, for identifying electron anti-neutrinos.

So, it has come about that people have accepted that water Cherenkov detectors are needed for higher energy neutrino studies and liquid scintillator instruments are deemed superior for lower energies.² As many peo-

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¹ Though some directionality may be obtained in a statistical way via the direction between positron annihilation and neutron cap-

ture in inverse beta decay. This was demonstrated by the Chooz Collaboration some years ago.

² There have been proposals to add water soluble materials

ple have seen, the SuperKamiokande cosmic ray neutrino interactions make very nice intuitive pictures with Cherenkov rings projected on the walls. Single clean rings result from the most frequent events due to $\simeq 1$ GeV quasi-elastic muon neutrino (and anti-neutrino) interactions. Fuzzy, shorter rings, more filled-in, result from electron initiated events of the same energy. Moreover, when pi-zero events are present, the pair of decay gammas often produce clearly distinct overlapping rings. In the search for nucleon decay, for example, the back-to-back signature of $p \rightarrow e^+ \pi^0$ may be easily recognized. Of course for higher energy neutrino interactions of a few GeV, life becomes more complicated, and one often cannot resolve much detail in the interactions (SuperK generally treats such as one single category called multi-ring events). This particle recognition capability has been very profitable for SuperK, and has resulted in the definitive discovery of muon neutrino oscillations in 1998, setting off the neutrino research gold rush of the last few years. New detectors in the megaton class are being considered for Japan, the US and Europe. In the following we will suggest that one may think about an alternative, or supplement, to consider very large scintillation detectors as well.

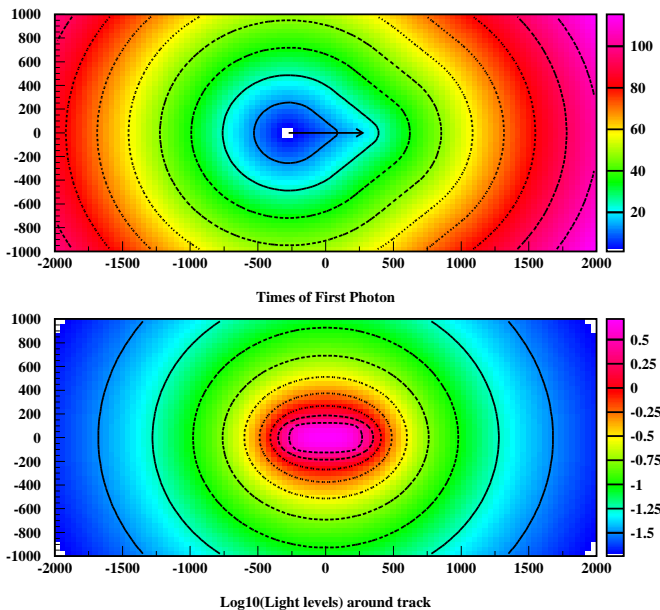


FIG. 1: These panels illustrate the time of first photon arrival (upper) and light level (lower) for a 547 cm long muon track in liquid scintillator in a 20m x 40m detector. One sees the asymmetric time contours due to photons on the Cherenkov cone. Times point to the start of the track, while amplitudes reveal the track center.

A. Scintillation Detectors Really are also Cherenkov Detectors for Higher Energies

Imagine a quasi elastic muon neutrino interaction in something like Hanohano or even KamLAND (or SNO+ or LENA), a single track of a few meters length. All researchers I know (including me) have been saying that all we would get is a nice calorimetric measurement³. One could measure total energy well, but nothing of direction or event topology. The realization herein (obvious *a posteriori*) that if one employs the earliest arriving hits on PMTs these will be on the light cone, and hence (by Fermat's Principle) will indeed have the timing as for a Cherenkov cone. Either side of the Cherenkov cone the light timing will be as from a point source, so it is this combination of partial spherical and cylindrical radiation that forms the "Fermat Surface". The greater the light, the better will be the approximation that the early hits are close to the Cherenkov time. For SuperK filled with liquid scintillator (and other possible detectors we will discuss) this would be hundreds of PE per tube for a 1 GeV event, and the earliest arrival will typically be within about one nanosecond of the lightcone. As is well known, this cone has wonderful directivity.⁴

B. There is plenty of light for first-in hit fitting

The trick here is that one can, with the relatively large event energies (say, GeV compared to MeV threshold sensitivity), get a hit nearly at the earliest possible time in almost every phototube. For example, if we take the sensitivity of KamLAND one would expect a total of $250 \text{ PE/MeV} \times 1000 \text{ MeV} / 2000 \text{ PMTs} = 250 \text{ PE/PMT}$ for a 1 GeV muon. (KamLAND has about a 20% photocathode coverage, and about a 20% quantum efficiency.) A 1 GeV muon will travel for a distance of roughly 500 cm, so on average the tubes will get about 1 PE from

(Gadolinium) to SuperKamiokande in order to make neutrons in inverse beta decay detectable. At the moment these plans are not progressing due to the corrosive nature of the Gadolinium salts. Even so, the electron anti-neutrino events below about 5 MeV are not likely to be accessible to SuperK, thus missing most of the reactor spectrum and essentially all of the geo-neutrinos.

³ Through-going muons are fitted by virtue of the evident entry point ("wound") in the response of the PMTs adjacent to the entry and exit points. Sanshiro Enomoto and Dan Dwyer of KamLAND have employed some timing of this type to fit through-going muons.

⁴ One concern for this first-in PE analysis is making sure that the PMTs have a low rate of prepulsing. Fortunately recent generations of PMTs do have very low rates of prepulsing. However, even if there is some prepulsing it can be dealt with through neighbor algorithms.

each 2 cm equivalent track segment (assuming isotropic radiation of photons from the track, as is the case). The geometric arrival time is spread over a time of order less than 60 ns, but somewhat more spread out due to scattering, absorption and re-emission, etc. Note that because of Fermat's Principle, no photon can beat the light cone, only fall behind it.

C. Real Cherenkov radiation will make some contribution

Depending upon the geometry, energy and scintillator, Cherenkov radiation may make a useful prompt light boost within the (small) solid angle of the tracks on the light cone. For an order of magnitude estimate, the equivalent Cherenkov radiation in KamLAND should be about $40 \text{ PE/cm} * 0.2 \text{ coverage} * 500 \text{ cm} = 4,000 \text{ PE}$ which will land in the tubes illuminated by the Cherenkov cone, which I would take to be for this case to be about $1/4$ on average. This is to be compared to roughly 60,000 PE from the scintillator light in the cone. Hence, very roughly I would expect that the in-cone Cherenkov signal will nearly double the first-in PEs from the scintillator. This is terrific: we can have a very good directional signal... we should be able to fit the direction of a quasi-elastic single muon quite nicely, as we demonstrate below. We did not include Cherenkov radiation in the simulations described herein in order to be conservative, but also there are complications in modeling the direct (and very blue) Cherenkov light which will be somewhat absorbed (and some re-emitted shifted towards the red). So, how much this improves the real world situation remains to be studied.

D. Other methods of event topology resolution

With this amount of light available it may well be profitable to install some cameras along with the photomultipliers. One may consider a small scale detector in which the light collected by commercial cameras would be substantial (eg. meter scale detectors observed with ≈ 10 cm lenses, possibly useful for reactor monitoring). However, for the very large instruments we focus upon herein, apertures on the scale of a substantial fraction of 1 m^2 would be needed. I will not pursue this line of thought here, but one may think about something like a version of the RICH detectors discussed by Tom Ypsilantis, with a spherical mirror and where the (spherical) focal surface is occupied by imaging or pixelated PMT. Pieces of Cherenkov rings are imaged as "moustache" shapes, while point sources will form point images, and a point moving across the field of view will image to a line. Depth of field is a problem, but solvable with multiple views (I

believe).⁵

II. GEOMETRY

Imagine a single muon moving horizontally (take it to be +x direction, rightwards) through the middle of a recumbent cylindrical detector (40 m long by 20 m in diameter), and which track extends some 5 m meters, starting at $x = -2.5\text{m}$ and travels to $x = +2.5\text{m}$. As the muon progresses it will produce lots of light, as said, but let us only consider the leading light. That light will be on the Cherenkov cone heading out in y and z, and heading off diagonally to the right (+x). Projected back to the track these first hit times will fit up, just as is done for Cherenkov cones in SuperK. But one will get something else too. Those PMTs to the left of the illumination zone of the Cherenkov cone will get hits from near the start of the track, and will fit to a nice spherical point-fit. Similarly those PMTs to the right, after the end of the track and Cherenkov cone, will also later receive hits on a spherical front centering on the end of the track. Hence, in principle, in this case (and every case for a single straight track) one can fit the all leading times with two point fits plus a Cherenkov cone, the Fermat Surface, as illustrated in Figure 1.

Do we have enough information? Of course, there are a few thousand illuminated PMTs each with a time and a total charge, and, most probably in a new detector, full waveform records. The fit is greatly overconstrained (7 or 8 unknowns and several thousand data points!). But this is not to prove that the information is not so smeared as to be impossible to extract. For example, the Fermat Surface (the equi-time countours, not to be confused with amplitude) represents the times of the nearest tracks, as in the case of multiple tracks from the same vertex. Only those track segments nearest the detector surface will register the time evolution for said track. Hence, for example, a quiver of tracks emanating from the same vertex point will only reveal the bounding track elements in the Fermat Surface. A track in the bunch center will be obscured. Hence we can conclude that from leading timing, no complex multi-track topology will be revealed. Of course, using the total light and hence energy deposited we may know roughly what was going on and a volume within which it was constrained, but no

⁵ I proposed using CCD cameras to image events in KamLAND at the collaboration in April 2005. The idea was partly to turn the imaging device invented by Makoto Sasaki for UHE cosmic ray work around and look inwards. Some simulation work was done by Byron Dieterle, and experimental tests have been conducted by groups at Tohoku University and at Kansas State university. Other work is progressing along these lines for directional low energy neutrino studies in various agencies. But until now, as far as I know, all this has been aimed at the few MeV energy regime.

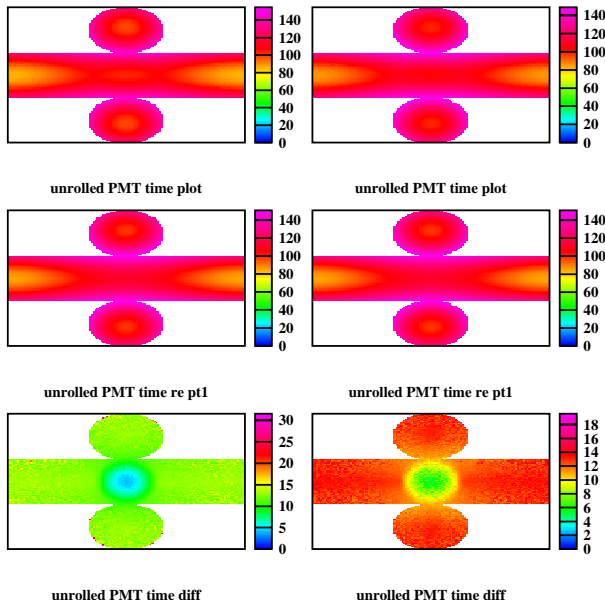


FIG. 2: These panels show first arrival times, for a muon on the left and an electron shower on the right. The top panels are the simulated data for a 1 GeV event (for the muon a 574 cm track). The second row shows times and amplitudes if the signal was from the interaction vertex. The lower two panels show the residuals between simulated data and point fits, illustrating the difference between a muon event and an electron induced event.

bubble chamber-like images can be extracted. (Which is also true of Cherenkov recordings as in SuperK of multiparticle final states). Yet, there is further information, buried in the multiple hits on each PMT. I hesitate to claim how well this can be used, since here will also lie all the complications of optical scattering, re-emission and so on. None-the-less, in Figure 3, one sees that there are gross differences between the photon arrival times for a muon track and for the same energy (1 GeV) electron shower.

In order to explore this I have written a small simulation program. The pretend detector is a right cylinder 40 m in diameter and 40 m high, $50,265 m^3$ and has a fill of next generation liquid scintillator (doped linear alkylbenzene, LAB, density 0.86) producing on average 10,000 detectable photons/MeV. I take it to have 7,377 phototubes each with a collection area of $0.4 m^2$, mounted on a 102 cm lattice. I ignore optical scattering and attenuation (not important for present purposes). In the program the muon is stepped long at the speed of light in vacuum while radiating 20,000 photons per cm, in random directions. Each photon is tracked towards the detector wall at the speed of light in vacuum divided by the index of refraction of the medium ($n = 1.482$). A resolution of 2 ns is inserted. The time of the first hit in,

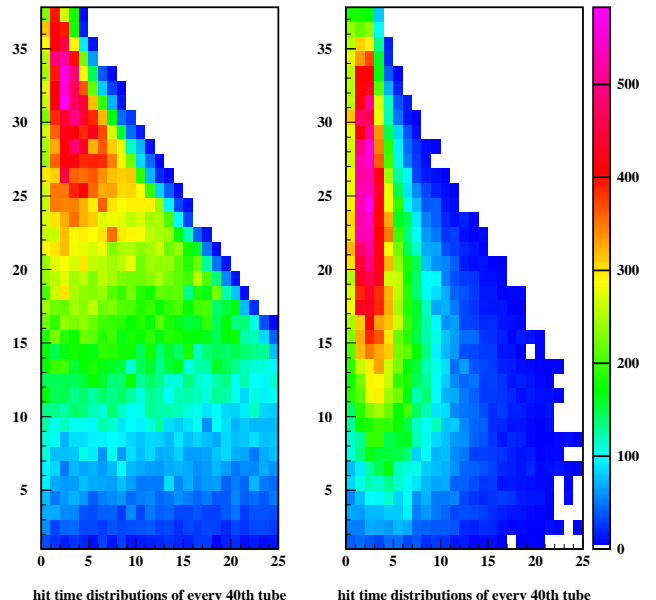


FIG. 3: A selection of individual time distributions for phototubes on the top of the 40 m x 40 m cylindrical detector studied, for a 1 GeV horizontal muon track and similar electron shower. The times are relative to the first photon for that phototube. One sees very significant differences in these distributions, and hence that there is much information to be potentially extracted from the individual photomultiplier record of pulse shape. Of course these are idealized plots with no optical scattering and such.

the total number of hits and the median time are saved for each PMT.

Exploring this “data”, I find that, as one may guess, a fit to the total charge collected for each PMT gives a nice determination of the track center, as illustrated in Figure 4. These panels are modelled on the SuperKamiokande unrolled view, with top folded up, bottom down, and the barrel of the cylinder unrolled. The simulated muon goes through the detector center and is pointed towards the back. The top panel shows the charge collected by each PMT, the second panel the charge expected from a point source of radiation of the same total amount of light, but radiating from the center of the track. The third panel shows the difference between these two data sets, and as one sees the point fit gives a very nice reproduction, indicating a simple means to start track finding. It turns out that calculating the “center of mass” of the detected charge (or photon levels) gives a good measure of the track center, without any fitting.

Figure 2 illustrates the data in terms of first-in photon time. The next panel down has the times as calculated from the beginning of the muon track. The lower left panel shows the difference between the top two, and such small residuals show that a point time fit reveals the track ori-

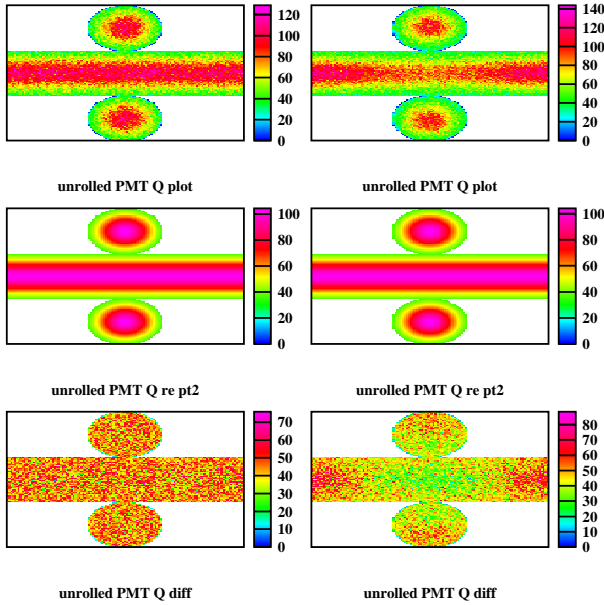


FIG. 4: These panels show charge collected for a muon event on the left and an electron event on the right. The top panels are the simulated data for 1 GeV events. The second row show amplitudes if the signal was from a point at the middle of the track. The lower two panels show the residuals between simulated data and point radiation, illustrating that point fits to the charge measured, reveal the middle of track very well.

gin fairly well. On the right side the same things are presented for a 1 GeV electron event.

I have tried a time based point fit, moving the test point, and this yields a point close to the beginning of the track (with a resolution of <10 cm, though systematically shifted by 80 cm, as illustrated in Figure 5. These fits are very useful as a method to find the first guess at a track. With development one can probably do better, but this does point towards a quick start to track finding.

The third fitting made was to the Fermat timing of a line (pseudo muon), defined by a starting and an ending point. A little geometric derivation yields the formula that the time from the start of the track to a point given by the vector \mathbf{R}_p , where the unit vector \mathbf{R}_t points long the track and the angle between track and PMT direction (given by $\cos(\alpha) = \mathbf{R}_p \mathbf{R}_t / |\mathbf{R}_p|$) is: $ct = |\mathbf{R}_p|[\sin(\alpha)\tan(\theta_C) + \cos(\alpha)]$. This makes for fast fitting, and some results are shown in Figure 5, two right hand panels, which show a χ^2 scan as a test track is moved along the ‘real’ track and as the test track is varied in angle with respect to the real track. The results encourage: the resolution in longitudinal fitting is about 1 cm, and in angle in about 0.2 degrees. Now perhaps these numbers are a bit optimistic, but it is clear that they are competitive with and perhaps even better than those for SuperK. (The SuperK-I single ring resolution

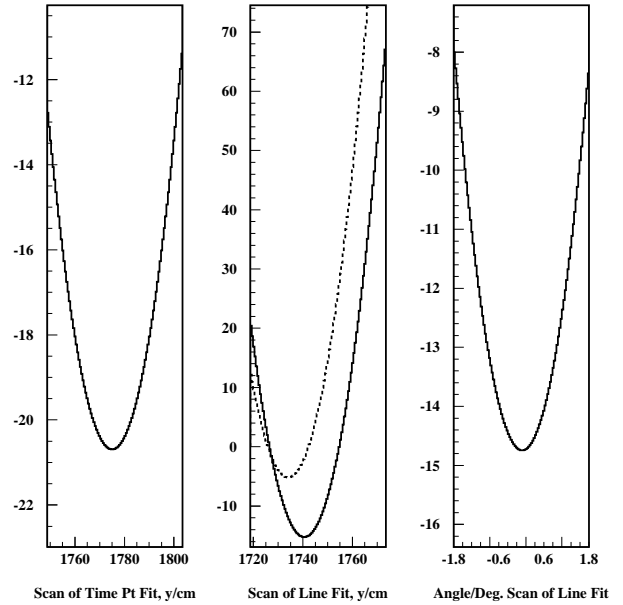


FIG. 5: Resolutions for point fits to time, at start of track; line to whole track; and varying angle of track. The line-fit scan shows the fit to an electron shower, on the same scale, which is about 11σ equivalent worse.

for e’s was 3 deg, μ ’s 1.8 deg[2]).

III. EXCELLENT ENERGY RESOLUTION TOO

If we collect 250,000 PE for a 1 GeV event, then the energy resolution could be as good as 0.2% for each event based upon Poisson statistics. Of course calibrations, non-linearities and such systematics will spoil this a bit, but it still will likely compare favorably with the SuperK momentum resolution for e’s of 3.2% and 2.5% for μ ’s at 1 GeV/c[2]. But is this possible advantage useful? It does mean that for events in which we know the source direction, as in T2K from the accelerator (or in LENA from CERN, or Hanohano as a long baseline experiment in the water near Korea), we may measure the energy and the angle relative to the direction towards the accelerator well, thus knowing the original neutrino energy, hence the L/E, whence facilitating precision measurements of muon neutrino oscillations. For comic ray neutrino studies the muon direction gives a conical locus of directions for the incoming neutrino, which is not as useful.

Since the fit of the initial point radiation (on the left in the situation described above and pictured in Figure 1) will yield the light near the start of the track we have the exciting prospect to deduce the energy of the nuclear recoil from the relative number of the early hits.

Of course the recoil nucleon will suffer from Birks saturation of the scintillator in its short energy deposition region, but clearly this is another area for study.

IV. FLAVOR DISCRIMINATION

In order to accomplish further interesting neutrino physics study it would be wonderful to be able to discriminate electron generated showers from muon tracks. We know the terrific success of IMB/Kam/SuperK in doing just this, simply based upon the fuzziness and extent of the Cherenkov cone. The EM shower builds quickly and flares towards the end and with increasing energy deposition (on average the longitudinal energy deposition profile may be approximated by a power law times a Gaussian), while the muon track energy deposition is more constant. Since the EM shower has more particles this effect somewhat fills the cone. But principally the electron shower is shorter as we move to higher energies: only a meter or so for electrons, compared to about five meters at one GeV for a muon. The electron shower may also reveal itself through the textural fluctuations in the Fermat Surface towards its tail.

The SuperK single ring electron detection efficiency is 90.2% and muon 95.8%, but most importantly only 0.4% of the muons are identified as electrons[2]. Fitting the simulated muon event to a line radiation yields about an eleven standard deviation (11σ) better fit than the same test function to a same energy simulated electron shower distribution. More careful simulation is assuredly needed here, and though the e/μ separation will deteriorate with lower energies and with inclusion of realistic optics, the author's sense is that the liquid scintillation detector will be quite competitive.

There may be some advantage as well, since for purposes of electron neutrino appearance, the most annoying background process is the single neutral pion production in the case that one of the two decay gammas goes nearly straight ahead and the second is unobserved. The scintillation detector might pick up either indications of the backwards photon and/or the recoil nucleon. However, this suggestion is assuredly speculative, and the author understands that work is needed.

I have made some preliminary investigations of flavor discrimination. One promising avenue is calculating the moment of inertia of the charge, weighted by time. The eigenvectors give a good first try at direction, and I find that the results for the same energy muon and electron are quite different (opposite directions), and this is with no fitting. I conclude that flavor separation will be good in the few hundred MeV to several GeV range. How good remains to be determined.

V. POSSIBLE APPLICATIONS

It would appear that this type of detector may have some significant applications, aside from the expected ones extrapolating from experience with KamLAND and SuperK employing studies of geoneutrinos, reactor neutrinos, relic supernova neutrino searches, remote reactor monitoring, etc.

A. T2KL

There is much effort going into the T2K, or Tokai to Kamoka, experiment, with a predicted rate of 3,900 events per year in 22.5kT SK for the first T2K configuration[4]. This may go up by a factor of 5 with an increased power accelerator beam later. If we just scale by factor of $1/22.5$ from SK to KamLAND there should be roughly 20 events per year in KL, or 100 events in five years (assumed for a T2K run). (This was for a 100 day year and 2 deg off axis[4]). So, does this give hope to do some good physics with KamLAND in the T2K beam? Having the rate down by 22.5x certainly hurts, leaving KamLAND uncompetitive for any θ_{13} work. Is there some advantage one may identify here? I suspect that there may be a good θ_{23} measurement (recall that the accuracy here has to do with fitting the period of oscillation, and errors are not simply Poissonian).

Of course it is always good to look for unusual physics... though I do not readily think of what that might be. Perhaps there is some physics which can be explored employing the incoming and uncontained events (where KamLAND is only down by a factor of six or so from SuperKamioande)?

In any event, KamLAND can assuredly provide a (free!) test bed for a much larger liquid scintillator experiment. The neutrinos will be there and presumably the signals collected. Timing will select true signature from background so whatever is seen should be clean of cosmic ray background.

B. Hanohano and LENA Long Baseline

One obvious application of large scintillation detectors comes immediately to mind: perhaps one may employ Hanohano in a long baseline run from Tokai, located in the water between Japan and Korea and forming a second location beyond Kamioka (and perhaps a third will be built in Korea). At 10,000 tons we would get about half the rate, and at those the distance it would fall to $1/8$ the rate of SK. This is still substantial, though larger would be better if HyperKamiokande is going to be built. Studies for Hanohano have indicated that mobile ocean based liquid scintillation detectors up to about 100 kilotons are practical from an engineering standpoint[7]. Note that for this application one does not need to be very deep (as is the case for geoneutrino studies, for example which

require 3 km or more of water overburden). The relatively large accelerator neutrino energies and the small duty cycle of the accelerator permits strong rejection of the cosmic ray background. Perhaps an alternative location would be in Lake Superior as a long baseline station from Fermilab, useful perhaps with Nova.

Similarly, the proposed LENA detector in Europe, at 50 kilotons, may now be considered as an end station for future CERN long baseline neutrino beams (in competition with a proposed few hundred kiloton water Cherenkov detector and a hundred kiloton liquid argon instrument).

C. WIMP Indirect Detection

For energies in the same 1 GeV range we are talking about, a large liquid scintillation instrument will certainly provide very nice detection of neutrinos. For indirect WIMP detection one should expect flavor democracy (plenty of time to equilibrate), and these events should point to the sun. If we really can get 0.2 degree angular resolution that would be terrific, but 1 degree would do. However the weak interaction scattering angle spoils nice pointing: having good angle determination for the muon does not help if the weak scattering angle is 20 degrees. Yet, having good energy and angle measurement means that the neutrino energy of any events from the solar direction will be well determined. Hence if we are so lucky as to have substantial WIMP annihilation to a two neutrino mode then this method may prove decisive in resolving the signature from the cosmic ray neutrino background. Again, this needs more work but it seems attractive, at least in the instance that the WIMP mass is not in the SUSY favored 100 GeV range, but rather in the few GeV range.

D. Nucleon Decay

There have been suggestions for some time to employ a large liquid scintillation detector for observing nucleon decay (for example with LENA[8]), particularly in the instance of SUSY favored modes involving a kaon which has kinetic energy too low to make Cherenkov light. With the present realization of the ability to study the directionality, the prospects are certainly improved. In order to compete with SuperK, probably a 100 kiloton

scintillation detector would be needed.

E. Astrophysics

Once again, there have been many searches for astrophysical phenomena discussed for smaller instruments and instruments with low thresholds. Aside from the WIMP search mentioned above, and extending searches as explored by KamLAND (relic supernova neutrinos, anti-neutrinos from the sun, bursts of low energy neutrinos from such sources as AGNs, micro-quasars, etc., a large liquid scintillation detector can enlarge the search for astrophysical neutrinos in the GeV range.

VI. SUMMARY AND OUTLOOK

The notion to employ a large liquid scintillation instrument as a detector which can accomplish similar physics to that which can be done with a large water Cherenkov detector has been sketched out. In some ways, for the GeV scale events, such a detector may equal or outperform the water Cherenkov instruments. Certainly liquid scintillation based instruments have the advantage of simultaneously being able to explore the lower energy range of electron anti-neutrinos due to reactors and geological origins, which are inaccessible to a water based Cherenkov detector. At the very least, I think we can conclude that this line of large neutrino detector consideration deserves further efforts.

VII. ACKNOWLEDGEMENTS

The idea in this note came out during conversations with Jason Kumar, and subsequent discussions with Shige Matsuno, Mikhael Batygov, Steve Dye and Sandip Pakvasa. Thanks to all. Also thanks to the AMANDA team whose use of first-in hits in fitting events in ice where the photon propagation is diffusive, probably put me in mind of this idea. Also thanks to Bob Svoboda who some years ago suggested converting SuperK to a liquid scintillation detector in his SCIPIO plan. And thanks to Sanshiro Enomoto and Dan Dwyer for their thesis work on through-going muon fitting in KamLAND.

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